

Western Port Seagrass Partnership

Mangrove Restoration in Western Port



December 2019

Cover Photo: Planted mangroves that have grown to maturity in a cove (Region 8A-7A) at Lang Lang South.

Mangrove restoration in Western Port.

Gregory D. Parry

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Western Port Seagrass Partnership

PO Box 2590

Mt Waverley, Victoria 3149

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Executive Summary

This report summarises the gradual refinement of planting techniques for mangrove seeds and seedlings by Western Port Seagrass Partnership, and many volunteers. Survival and growth of mangroves was monitored at three sites in Western Port (Grantville, Lang Lang North and Lang Lang South) to determine which planting methods worked best. Unfortunately, improving planting methods is a slow process, as each new method takes a minimum of 12 months to evaluate.

Mangroves planted in protective tubes had higher initial survival, but those protected from waves with “pipe pile fields” had lower survival. Addition of artificial turf to the rim of protective tubes to minimise ring barking resulted in no measurable improvement in survival. Mangroves planted further offshore usually had lower survival. This is likely to make establishing a broad band of mangroves more difficult.

Survival and growth of mangroves was similar at Grantville and Lang Lang South, but lower at Lang Lang North. The similarity of survival at Grantville and Lang Lang South occurred despite historical records showing that mangroves were removed from Grantville, but never grew at Lang Lang South (Smythe 1842). It appears that habitat suitable for establishing young mangroves is patchy on a small spatial scale. Variation in survival between plots within the

Grantville and Lang Lang South sites was greater than variation between these sites. Many of the factors responsible for this variation remain to be determined.

The causes of mortality of mangroves at Grantville remain uncertain, although wave energy is a major factor, as protection within tubes increases seedling survival. Unfortunately, until the tubes were re-designed recently, tubes also caused significant mortality when removed.

Survival was variable along the Lang Lang South coast, with strong growth and low mortality near the Lang Lang River and very low mortality in the two largest coves. Elsewhere adjacent to steep cliffs mortality was high, probably due to high wave energy, fluid sediments, or both. It seems unlikely that mangroves will establish adjacent to steep cliffs at Lang Lang South without additional protection from waves, although it remains unclear how much mangrove mortality is directly due to waves.

While the highest survival was achieved with 12 month old seedlings, high initial survival was also achieved with seeds. Further work is required to optimise the staked seed method as growing mangroves from seeds is much cheaper, making large-scale restoration more feasible. In addition, direct seeding does not rely upon limited expertise to on grow seedlings in a nursery.

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Introduction

Western Port Seagrass Partnership, in conjunction with many volunteers, commenced planting mangrove seedlings in 2005 to reduce coastal erosion, a major source of sediment entering Western Port. Mangroves were planted north and south of Lang Lang River, and at Grantville.

When Western Port was surveyed in 1835 (Smythe 1842) mangroves were growing at Grantville, but not at Lang Lang. Consequently, Grantville provided a better site for developing techniques for mangrove establishment, as there was historical evidence that this site contained suitable mangrove habitat. While Lang Lang was a more challenging site for establishment of mangroves, the need for coastal protection was greater there, as erosion of cliffs along 9 km of this shoreline is the source of ~30% of sediment inputs to Western Port (Wallbrink et al. 2003, Wilkinson et al. 2016).

Developing methods to successfully establish mangroves is a slow process. Mangroves grow slowly and seeds are only available for

propagation for a few weeks each summer. Evaluation of each new growing method requires a minimum of 12 months to measure the survival of plants. There also remain many environmental factors that may influence the survival of mangroves, including wave action, sediment type, salinity of ground water, distance offshore, proximity of other mangroves, nutrient availability and barnacle settlement. Consequently, the best method of establishment is likely to vary between locations, further complicating the evaluation of methods.

Between 2005-2014, seedling survival improved as various methods were trialled, but detailed records of survival and growth were not maintained.

This report deals mostly with the survival and growth of seeds and seedlings planted between 2015-2019 at three sites in Western Port: Grantville, Lang Lang North and Lang Lang South. However, the survival and growth of seedlings planted before 2015 are also reported for the period 2015-2019.

Materials and Methods

2005-2014 plantings

Between 2005-2014 mangroves were planted at Grantville, Lang Lang North and Lang Lang South (Figure 1). Many different methods of growing mangrove seedlings and seeds were trialled during this period, but most seedlings were grown from seeds in 600 mL milk cartons at Mornington Peninsula Youth Enterprises nursery. Each seedling was planted, when three months old, in its carton, after the bottom of the carton was opened. Seedlings were usually planted in three rows 1 m apart parallel to the coast.

Detailed monitoring of survival and growth of these mangroves commenced in 2015, when the Lang Lang South and Grantville plantings were divided into discrete regions, each 50-200 m long, and separated by geographic features, such as the junction between a cove and a cliff. The survival and growth of mangroves in each region was monitored each subsequent May and November, until May 2019. None of the mangroves planted between 2005-2013 at Lang Lang North were still alive in 2015.

Many seedlings planted in milk cartons pre-2015 survived well, but it became apparent that the plastic lining of the carton degraded only slowly, often inhibiting the growth of lateral roots (Figure 2) and compromising their long term survival. After 2015, except for two experimental plots, all mangrove seedlings were removed from milk cartons prior to planting.

2015-2019 plantings

Between 2015 and 2018, seedlings and seeds were planted at three sites in Western Port (Grantville, Lang Lang North and Lang Lang South, Figure 1). No seeds or seedlings were planted in 2019, as mangrove seeds were very scarce throughout Western Port during summer 2019.

At each site seedlings or seeds were planted in marked plots that contained 100 (occasionally 50) seedlings or seeds (Figure 3). All seeds and seedlings were planted 1 m apart in a grid of 4 rows, which were also 1 m apart. A typical plot was ~25 m × 4 m.

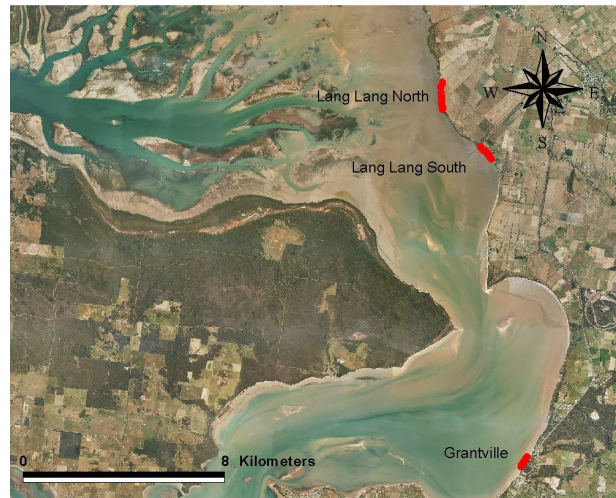


Figure 1. Location of the three main sites at which mangrove seedlings and seeds were planted in Western Port between 2005-2019.



Figure 2. A 70 cm high mangrove at Grantville in 2016, when approximately 4 years old, showing the spread of pneumatophores constrained by the plastic lining of the milk carton in which it was planted.

Hurst (2013) found that seedlings had higher initial survival when planted within protective 100 mm diameter PVC tubes. However, over a 12 month period his tubes acted as sediment traps, causing seedlings to be progressively buried. Consequently, we modified his tube design, by

including four longitudinal slots (Figure 3), which prevented sediment from accumulating within each tube. These tubes were inserted ~100 mm into the sediment so that the lower edges of the four slots were level with the surrounding sediment (Figure 3).



Figure 3. Marked plot in which 100 seedlings were planted at Lang Lang North, showing cattle ear tags used to mark plots and the slotted tubes used for protecting mangrove seedlings and seeds between 2015 and 2018.

In 2018, a new tube design was trialed as it was found that removal of pipes inserted 100 mm into the sediment caused root disturbance that killed many seedlings. New tubes extended only ~25 mm into sediment and were held in place using five 700 mm bamboo stakes, which were attached to the tubes using cable ties (Figure 4).



Figure 4. Tube design used after 2018. Tubes were inserted only 25 mm below the sediment, and secured by 700 mm bamboo stakes and cable ties.

Seedlings

Seedlings were grown at Advance Nursery (formerly the Mornington Peninsula Youth Enterprises Nursery) from seeds harvested from sites in Western Port (Jam Jerrup, Pioneer Bay, Rhyll, Tooradin) between late December and early February in 2015, 2016, 2017 and 2018. Care was taken to collect only ripe seeds. i.e. seeds that broke off plants with minimal force, or had been naturally shed recently. Seeds were on-grown in 25% seawater at the nursery, and subject to daily draining to simulate tidal flushing, until they were planted.

Seedlings were planted either in April or May, after they had grown in the nursery for approximately 3 months, or between November and February, when they had grown in the nursery for 9-12 months.

At Grantville, three month old seedlings were planted at 10 plots, and 9-12 month old seedlings planted at 18 plots on dates shown in Table A1. All were planted inside PVC tubes (Figure 3), except at two plots planted in May 2015 (Table A1).

At Lang Lang North, three month old seedlings were planted at 20 plots in April 2015 and 9-12 month old seedlings were planted at 5 plots in January 2015 (Table A2). All were protected by PVC tubes, and three plots (Plots 7, 8 & 14, Figure 21) were additionally protected by wave barriers created by Hurst (2014) using “pipe pile fields” consisting of many ~2 m long PVC pipes (Figure 5).



Figure 5. One of three plots at Lang Lang North protected from waves by a “pipe pile field” of ~2 m PVC pipes, established by Hurst (2014).

At Lang Lang South, three month old seedlings were planted at 15 plots in April 2016 and 9-12

month old seedlings were planted at 12 plots on dates shown in Table A3.

Once mangroves grew higher than their protective tubes they often became ring-barked by the edge of the tube, and then broke off at the tube edge (Figure 6).



Figure 6. Mangrove plant ringbarked, then broken off, after it grew above the level of the protective tube.

Consequently, experiments were undertaken in which (1) tubes were removed once most mangroves on a plot were higher than their tubes, and (2) a strip of artificial turf was attached on the inside of each tube (Figure 7) on selected plots, and survival and growth on these plots were compared to control plots. The plots and dates upon which these experiments were conducted are shown in Tables A1 and A3.

Effect of tubes on seedling survival

The effect of tubes on survival was tested at Grantville in May 2015 when 2 plots were planted without tubes, and 5 plots were planted with tubes (Table A1).

Effect of tube removal and addition of artificial turf on survival of seedlings

Experiments to measure the effect of tube removal and the addition of artificial turf to tube margins on mangrove survival were undertaken at Grantville and Lang Lang South. Tubes were removed or turf added approximately 12 months after planting, on dates shown in Tables A1 and A3.



Figure 7. Ring of artificial turf, attached by foldback clips around the rim of the protective tube, to prevent ring barking.

At Grantville tubes were removed from 2 of 3 plots planted during January 2015 ; from 1 of 3 plots planted during April 2016; tubes were removed from 2 plots and turf added to 1 plot of 5 plots planted during November 2015; turf was added to 6 of 10 plots planted during December 2016 and January 2017 (Table A1) .

At Lang Lang South tubes were removed from 2 plots and artificial turf added to 1 of 5 plots planted during April 2016; turf was added to 5 of 11 plots planted during January and February 2017 (Table A3).

All remaining tubes from Grantville and Lang Lang South were removed in early 2019, as it had become clear that tubes prevented growth of lateral roots. Tubes were removed to minimise root inhibition, although the process of removing tubes killed many plants.

Seeds

Once the seed coat is removed from a mangrove propagule, the cotyledons are evident. The propagule could therefore be considered a seedling rather than a seed. The term seed is used in this report to mean the “seed-like” mass evident as soon as the (floating) outer coat is removed.

Seeds are only ripe between December and February and were planted in January 2015, January 2016, January 2017 and January and February 2018. Mangroves seeds were scarce throughout Western Port during summer 2019.

In January 2015, seeds were inserted to approximately half their length in sediment within slotted PVC tubes. Seeds were planted at

three plots at Grantville and at three plots at Lang Lang North (Table A5).



Figure 8. Mangrove seed held in place by double layer of 9 mm meat netting inside a slotted PVC tube (upper). Device used to insert builders spacers and a single layer of 15 mm meat netting to hold seeds in place (lower).

In January 2016, seeds were held on the sediment surface by a double layer of 9 mm meat mesh which was held in place by U-shaped 2 mm thick builders spacers (Figure 8). Seeds were planted at five plots at Grantville and at one plot at Lang Lang North (Table A4).

In January 2017, seeds were planted either beneath a single layer of 9 mm meat netting or a single layer of 15 mm meat netting. Seeds were planted at eight plots at Grantville and two plots at Lang Lang South (Table A5). Seeds were planted within tubes in which seedlings had been planted previously, but had died.

In January and February 2018, seeds were planted using a new technique developed by John Eddy. Each seed was attached to a 750 mm × 8-10 mm diameter bamboo stake using a No 12

Esselte rubber band (40 mm × 1.5 mm). The rubber band held the seed for ~30 days while the roots developed (Figure 9).



Figure 9. Mangrove seed attached to a bamboo stake by a rubber band while roots developed.

After ~30 days the rubber band had usually deteriorated and released the seed, which was then held in place by its roots alone. Seeds were planted at four plots at Grantville (Plots 2, 3, 12, 13), and two of these plots (Plots 3, 12) were protected using re-designed slotted tubes (Figure 4) during April 2018. Seeds were also planted at 4 plots at Lang Lang South (Plots S1, S5, P9, P10), and while few of these survived, the five survivors on Plot S5 were also protected by re-designed slotted tubes in April 2018 (Table A4).

Effect of location on survival of seedlings

Annual survival on all plots was estimated from counts of survivors (undertaken in May and November of each year) over the first 400-500 days after planting. Annual survival was estimated from the gradient of Log_e (No. of Survivors) vs time regressions, and subsequently shown as % annual survival.

Results and Discussion

Seedlings from 2015-19 plantings

Effect of tubes on seedling survival

Survival of 3 month-old seedlings planted at Grantville in May 2015 was much lower when planted without tubes (Figure 10).

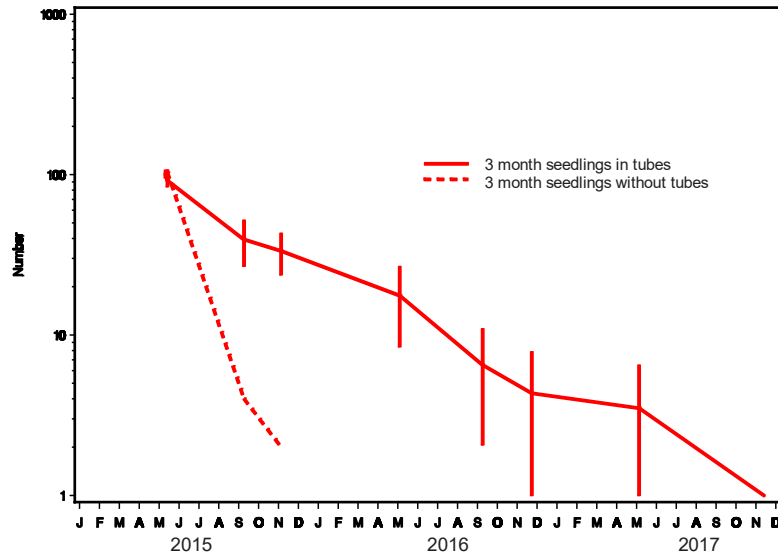


Figure 10. Comparison of survival of 3 month old seedlings planted at Grantville in May 2015 in tubes and without tubes.

Effect of wave protection by pile fields on mangrove survival

Seedlings planted behind pile fields to attenuate waves had (unexpectedly) lower survival than those not so “protected” (Figure 11). Hurst (2013) also observed lower survival of seedlings behind these pile fields, but his data was difficult to interpret as the pile fields provided protection for only one to five months before his experiment was terminated. Furthermore, seedling survival in his experiments may have been affected by sediment disturbance during the insertion of the pile fields.

Survival of seedlings behind the same, but now well-established, pile fields clearly shows they

reduced rather than increased survival of mangrove seedlings. This suggests that reducing wave energy does not necessarily improve survival of mangroves, or more likely, there are other factors at play.

Dark discolouration of leaves of seedlings occurred behind the pile fields. This may be due epiphytic algal growth potentially stimulated by sediment borne nutrients (Figure 12A). Similar discolouration occurred within the protective tubes and on the pile field itself (Figure 12B), and may have contributed to the higher mortality behind the pile fields.

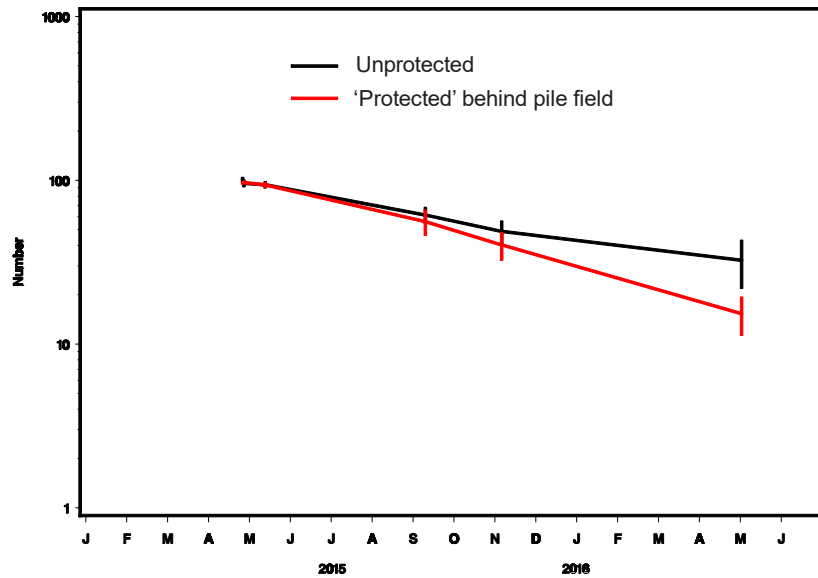


Figure 11. Mortality of 3 month old seedlings at plots protected from wave action by “pile field” (see Figure 5) (N= 3 plots) and unprotected plots (N=10 plots). Error bars are standard errors.

A.



B.



Figure 12. A. Mangrove behind pipe field showing algal growth/sediment accumulation on lower leaves and on inside of protective tube, B. Pipe field showing similar (?) algal growth on pipe field.

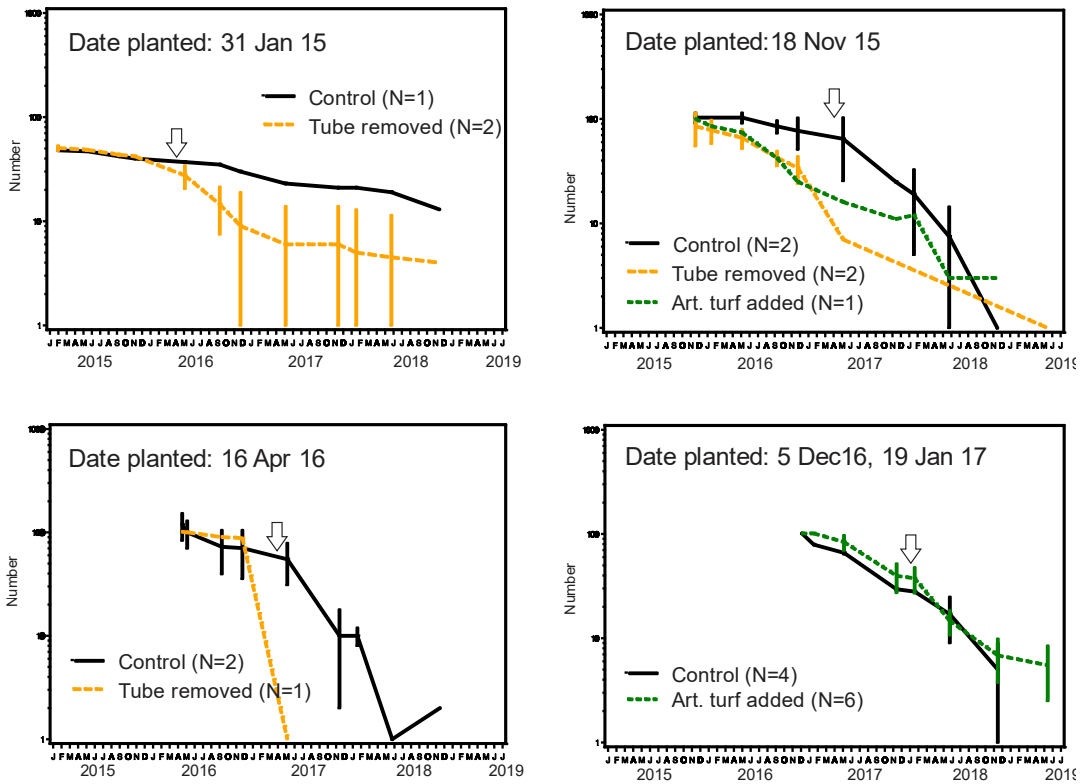
Effect of tube removal and artificial turf addition to mangrove survival

Mangrove survival declined sharply as soon as protective tubes were removed at both Grantville and Lang Lang South (Figure 13). Mortality was often immediate. At Grantville up to 50% of seedlings on a plot became prostrate immediately tubes were removed, probably as their tap root was broken as tubes were extracted. While at Lang Lang South sediment had often eroded around the tubes, so that upon the removal of the

protective tube the seedling and its surrounding sediment were higher than the level of the surrounding sediment (Figure 14). This sediment eroded quickly causing the loss of the seedling. Tubes also truncated the growth of some lateral roots (Figure 15), and the confined lateral roots to within the tube (Figure 16) and led to high rates of loss upon removal of tubes.

Addition of artificial turf did not clearly improve seedling survival (Figure 13), although there was large variation in survival between plots, making it difficult to detect small effects.

A. Grantville



B. Lang Lang South

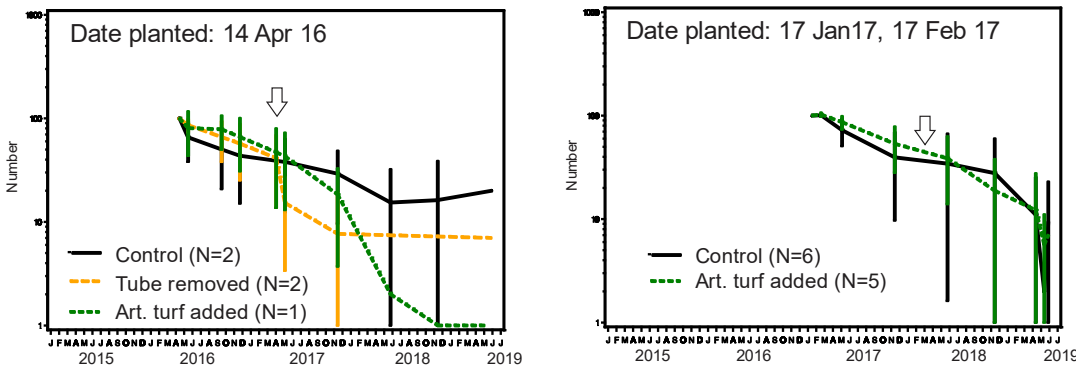


Figure 13. Plots showing effects of tube removal and attachment of artificial turf on survival of batches of mangrove seedlings planted on different dates at A. Grantville and B. Lang Lang South. Arrows indicate when tubes were removed and/or artificial turf was added. N is the number of replicate plots in each treatment.



Figure 14. A plot at Lang Lang South immediately after PVC tubes were removed from mangrove seedlings showing the extent to which sediment had eroded from the plot since tubes were inserted.



Figure 15. A semi-prostrate mangrove at Lang Lang South after its protective tube was removed, showing a large diameter lateral root that appears to have stopped growing when it reached the tube.



Figure 16. A mangrove seedling at Lang Lang South about to be washed away, showing the confinement of lateral roots to within the PVC tubes.

Regional differences in survival and growth

Survival of 3 month old and 9-12 month old seedlings planted at Lang Lang North was usually lower than survival at Grantville and Lang Lang South (Figure 17), except that 3 month

old seedlings planted at Grantville in May 2015 had exceptionally low survival (Figure 17A). This low survival was probably due to these seedlings being much smaller when planted out (Figure 18A), as they had failed to thrive in the nursery.

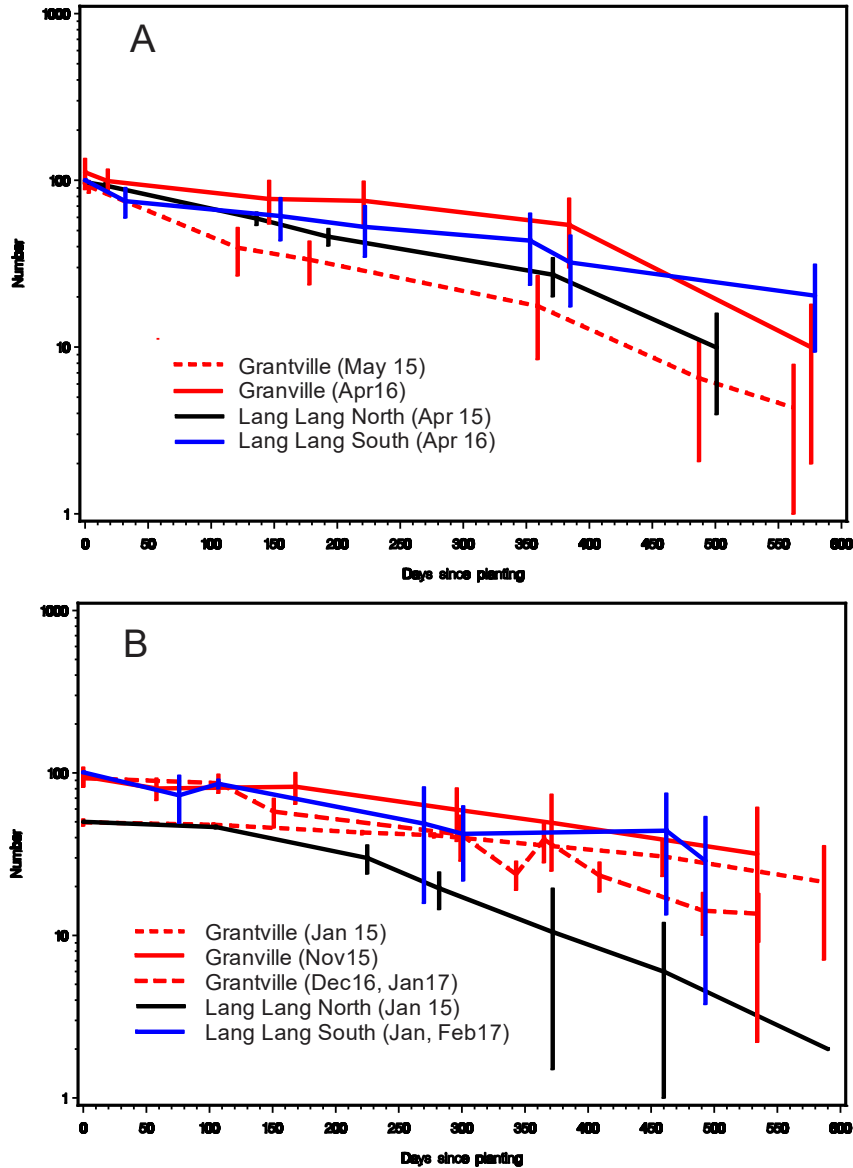


Figure 17. Survival of A. 3 month old mangrove seedlings and B. 9-12 month old seedlings from each planting at Grantville, Lang Lang North and Lang Lang South. Error bars are standard errors.

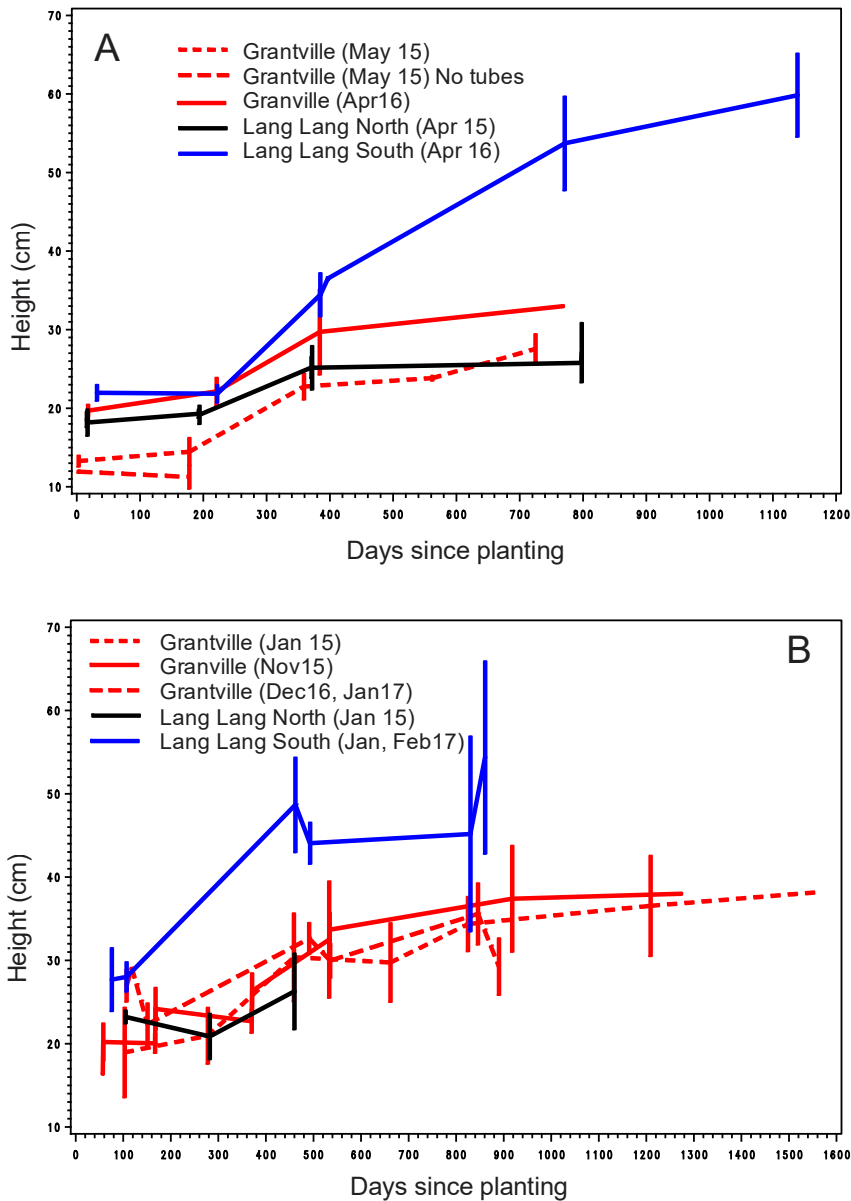


Figure 18. Growth of A. 3 month old mangrove seedlings and B. 9-12 month old seedlings from each planting at Grantville, Lang Lang North and Lang Lang South. Error bars are standard errors.

Seedlings without tubes did not grow (Figure 18A) and had very low survival (Figure 10). Both survival and growth were low at Lang Lang North (Figures 17 & 18). Survival was usually similar at Grantville and Lang Lang South, but growth was faster at Lang Lang South (Figures 17 & 18).

The mean height of mangroves a year after planting ranged from 22-34 cm, for those planted when 3 months old, to 22-45 cm, for those planted when 9-12 months old. The fastest growing seedlings were approximately 50 cm

high 2 years after planting and approximately 60 cm high 3 years after planting.

Small-scale spatial differences in survival and growth within sites

Grantville

At Grantville there was much variation in survival between batches planted at different times and plots, and few clear patterns in survival. Temporal and spatial effects were difficult to distinguish.

The clearest pattern was that 3 month old seedlings planted in May 15 had lower survival than all other seedlings (Figure 19). The poor survival of these seedlings was probably due to their small height when planted (Figure 18A).

There were no clear spatial differences in survival within the ~ 450 m section of coast planted.

A hard layer of peat occurred beneath a layer of sandy mud on all plots. Survival appeared lower where the sandy muddy layer was very thin, and further offshore where the muddy layer was thick, but very soft. Further measurements are required to test the veracity of these observations.

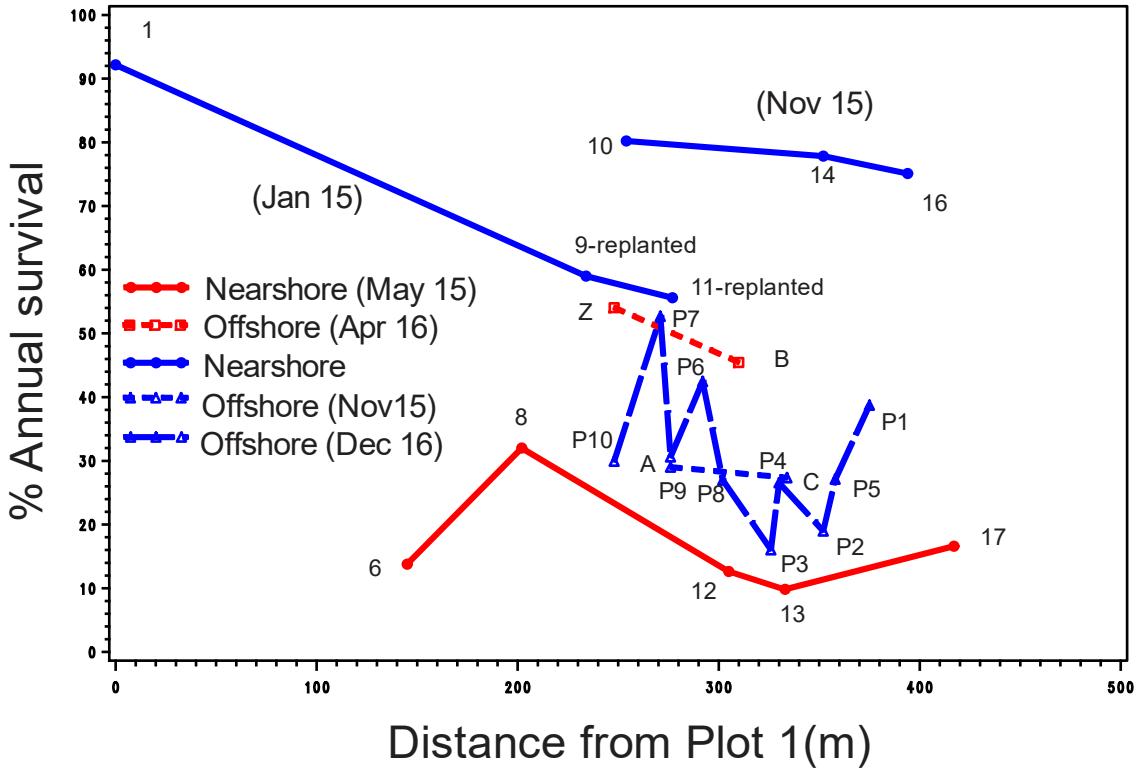


Figure 19. Annual % survival of mangrove seedlings planted on different plots at Grantville when 3 months old (RED) and 9-12 months old (BLUE) planted onshore and offshore on the dates shown. Numbers and letters identify the plots, which are shown in Figure 20.

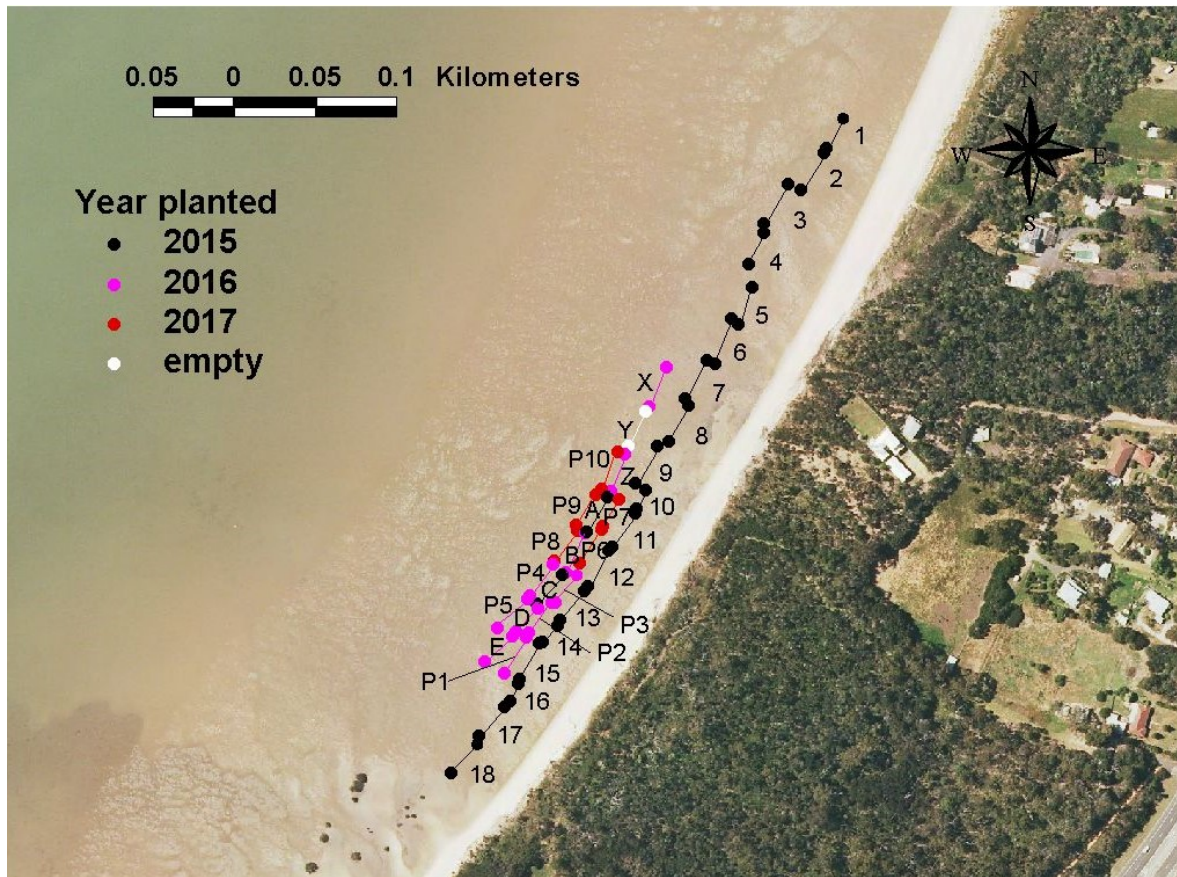


Figure 20. Location of all plots planted with seedlings or seeds at Grantville between 2015 and 2017.

Lang Lang North

Survival on plots at Lang Lang North was lower than at Grantville and Lang Lang South. This is consistent with low survival of pre-2015 plantings at Lang Lang North. In 2015 there were no mangroves surviving at Lang Lang North from pre-2015 plantings, while there were many survivors at Grantville and Lang Lang South. There had been at least 5000 seedlings planted at Lang Lang North pre-2015, based on a count in 2015 of stakes planted with each seedling.

At Lang Lang North survival was not clearly different adjacent to cliffs than within coves, nor was the survival of 9-12 month old seedlings higher than that of 3 month old seedlings (Figure 21). The three plots behind the pile forests all had lower survival than adjoining plots (Figures 11 & 21).

At Lang Lang North there was lower survival with distance south of Plot 1 (Figure 21). The decline in survival from north to south was probably due to increased as wave energy.

However at the northernmost cove, the plot with the highest survival, ground water adjacent to coves may have had lower salinity, and this may have also increased survival. Barson and Bird (1975) suggest that the crenulate coast at Lang Lang (North and South) may be a historical legacy of the Koo Wee Rup swamp, where coves were maintained by floodwaters which spill out of the swamp. This is consistent with the observation that the highest survival occurred at Plot 1, but between Sep16 and Jul 17 many mangroves on this plot perished when a flood cut a 5 m wide swathe through the plot, eroding sediment and washing away many mangroves (Parry, pers obs).

At Lang Lang North mangroves were also planted directly into the firm peaty basement layer, and it is unclear if this is a suitable mangrove habitat. While the peaty layer existed at the other two sites it was overlain by muddy sand sediment of variable thickness at Grantville, and fine muddy sediments of variable fluidity at Lang Lang South.

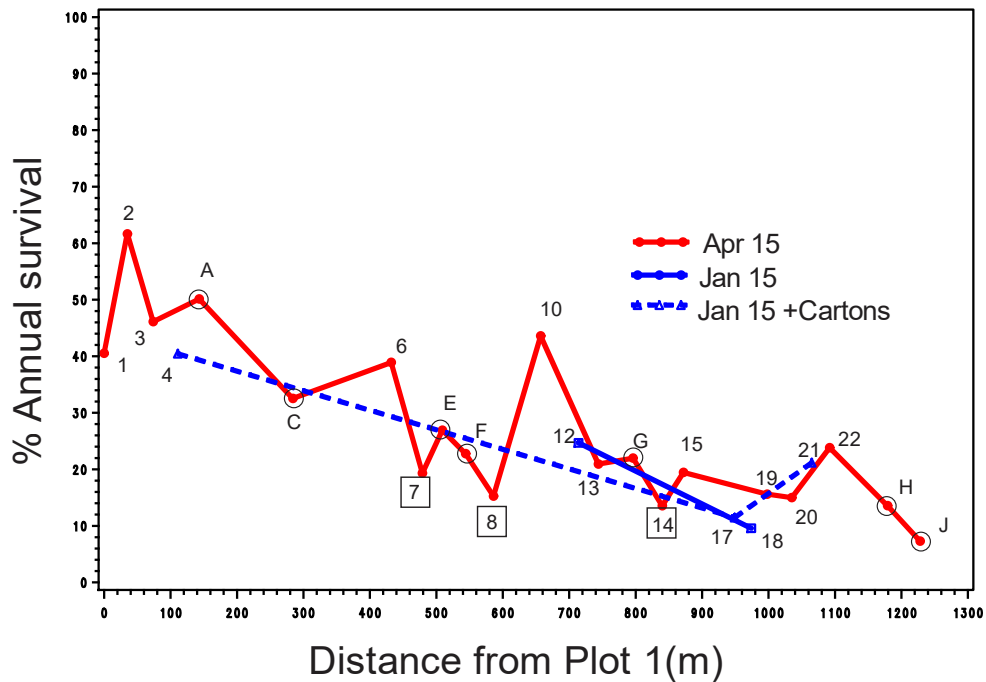


Figure 21. Annual % survival of mangrove seedlings planted on different plots at Lang Lang North when 3 months old (RED) and 9-12 months old (BLUE). All were planted onshore and the dates seedlings were planted are shown. Numbers and letters identify individual plots and the location of each plot is shown in Figure 22. Seedlings were planted in plots 4, 17 and 21 in tubes in the cartons in which they were grown. Circles indicate plots adjacent to cliffs, while all other plots were in coves (Figure 22). Squares indicate plots behind a field of pipes (Figure 5).



Figure 22. Location of all plots planted with seedlings or seeds at Lang Lang North in 2015

Lang Lang South

At Lang Lang South 9-12 month old seedlings had higher survival than 3 month old seedlings. 9-12 month old seedlings had higher survival onshore than those planted (slightly) further offshore (Figure 23A). Most 3 month old seedlings were planted onshore, so differences between survival onshore and offshore were not evident. (Figure 23A).

At Lang Lang South rates of survival in plots planted between April 16 and Jan-Feb 17, were compared to the survival of mangroves which had been planted pre-2015, along segments of the same coastline (Table A4).

The highest survival of 3 month old seedlings was in the region between SA and SD (Figures 23A & 24). This region was closest to the Lang Lang River, where there was less fluid mud, possibly as adjacent cliffs were eroding more slowly than other cliffs.

3 month old seedlings in the region between SE and SH had very low survival (Figure 23A). Mangroves in this same region (7A-7) from pre-2014 plantings also had low survival (Figure 23B). Survival was also low on Plot SH (Figure 23A), which was within in region 6-5, where survival of pre-2014 plantings was also low (Figures 23B and 24). Both regions 7A-7 and 6-5 had low survival and occurred adjacent to steep cliffs (Figure 25). Sediments adjacent to these cliffs were soft and fluid, possibly due to erosion of the cliffs. Mangroves roots may be unable to anchor the plant in this soft mud and the very

fine mud may interfere with their ability to obtain oxygen via their pneumatophores.

In 2015 there were a few large (>1 m high) mangroves along the Lang Lang South coast (Figure 23B). These mangroves were so large they must have recruited before WPSP commenced planting in 2005. In 2019, they were 10-18 m offshore from the base of the nearest cliff. They probably established naturally ~20-30 years earlier, when they would have been 6-9 m closer to the receding cliffs, assuming an erosion rate of 30 cm/year (Wilkinson et al. 2016). These large mangroves now occur in very soft sediment where further natural recruitment seems unlikely. These observations suggest there may be only a narrow band of shoreline in which mangrove establishment is possible.

Plots close to shore (P4, P13) and protected in coves (P4, P8, S2, S3) showed the highest survival. These regions seldom or never were covered in soft fluid mud, which in other areas exceeded 50 mm deep.

Mangroves planted within the cove between markers 8A and 7A (Figure 25) had high survival, provided they were in the north western half of the cove. Survival of larger mangroves planted pre-2015 was nearly 100% in regions 8A-8 and 8-7B. Sediments were firm in this region, but much softer and more fluid to the south east of the cove.

There were no clear patterns in growth of mangroves from different regions at Lang Lang South (Figure 26).

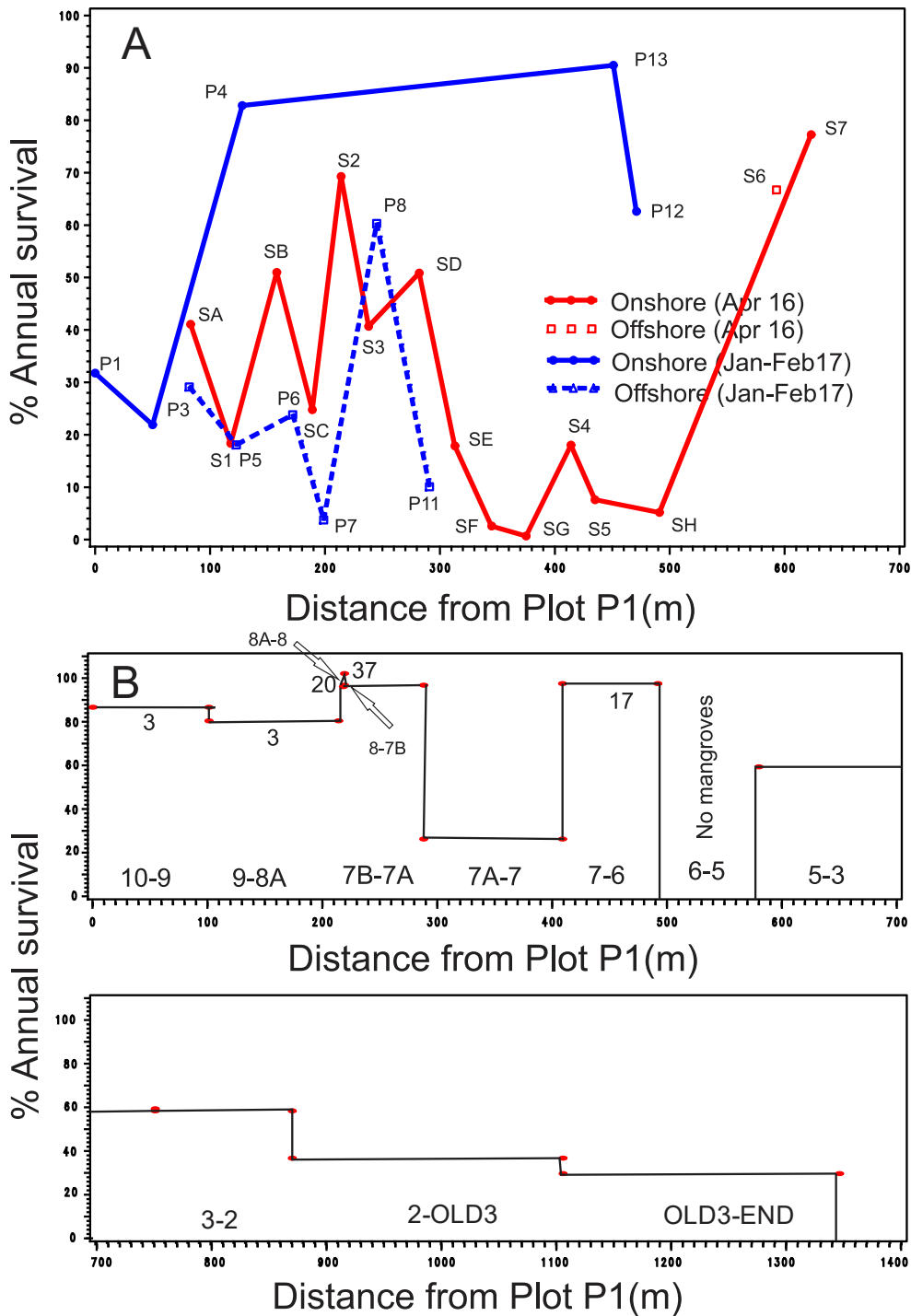


Figure 23A. % Annual survival of mangrove seedlings planted on different plots at Lang Lang South when 3 months old (RED) and 9-12 months old (BLUE). Seedlings planted inshore and slightly further offshore are shown. Numbers and letters identify plots in the location of which are shown in Figure 23. B. % Annual survival of mangroves planted pre-2015 in different sectors of the Lang Lang North coast shown in Figure 25. % survival is based on all mangroves in each sector, but two cohorts (<1 m and 1m+), planted at different times, were evident. The number of mangroves higher than 1 m in each sector is shown.

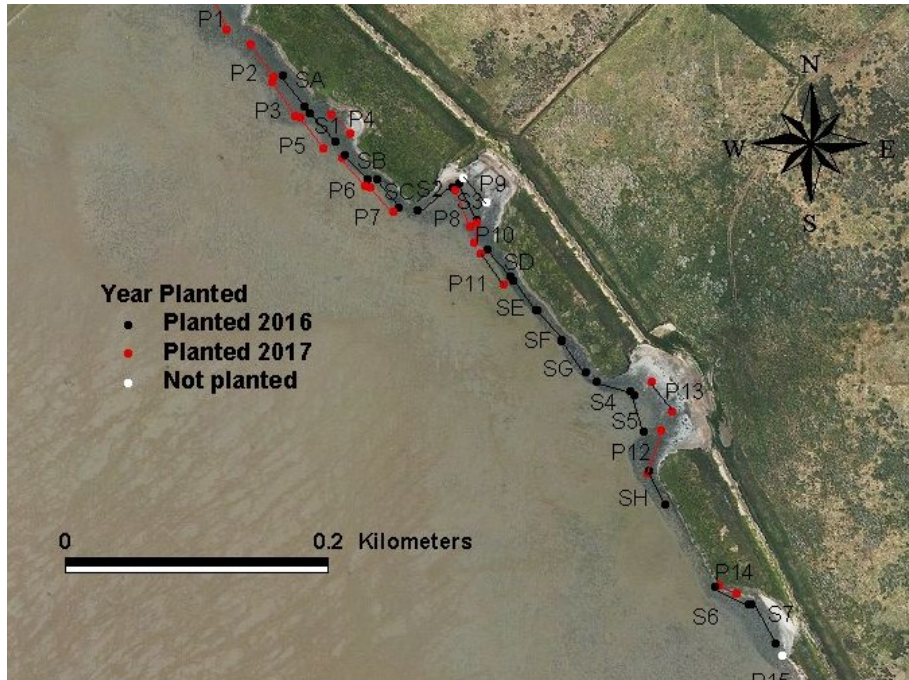


Figure 24. Location of all plots planted with seedlings or seeds at Lang Lang South in 2016 and 2017.

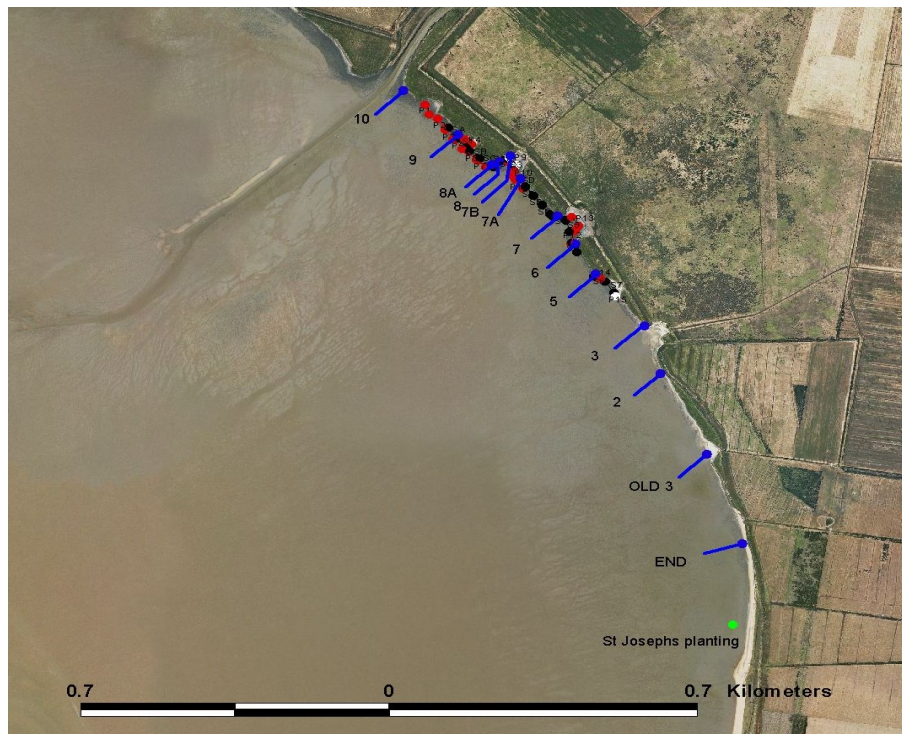


Figure 25. Location of all regions planted with seedlings or seeds at Lang Lang South before 2013, where survival and growth were measured between 2015-19. Note Plot P9 occurs between markers 8A and 7A, while plot P13 occurs between markers 7 and 6.

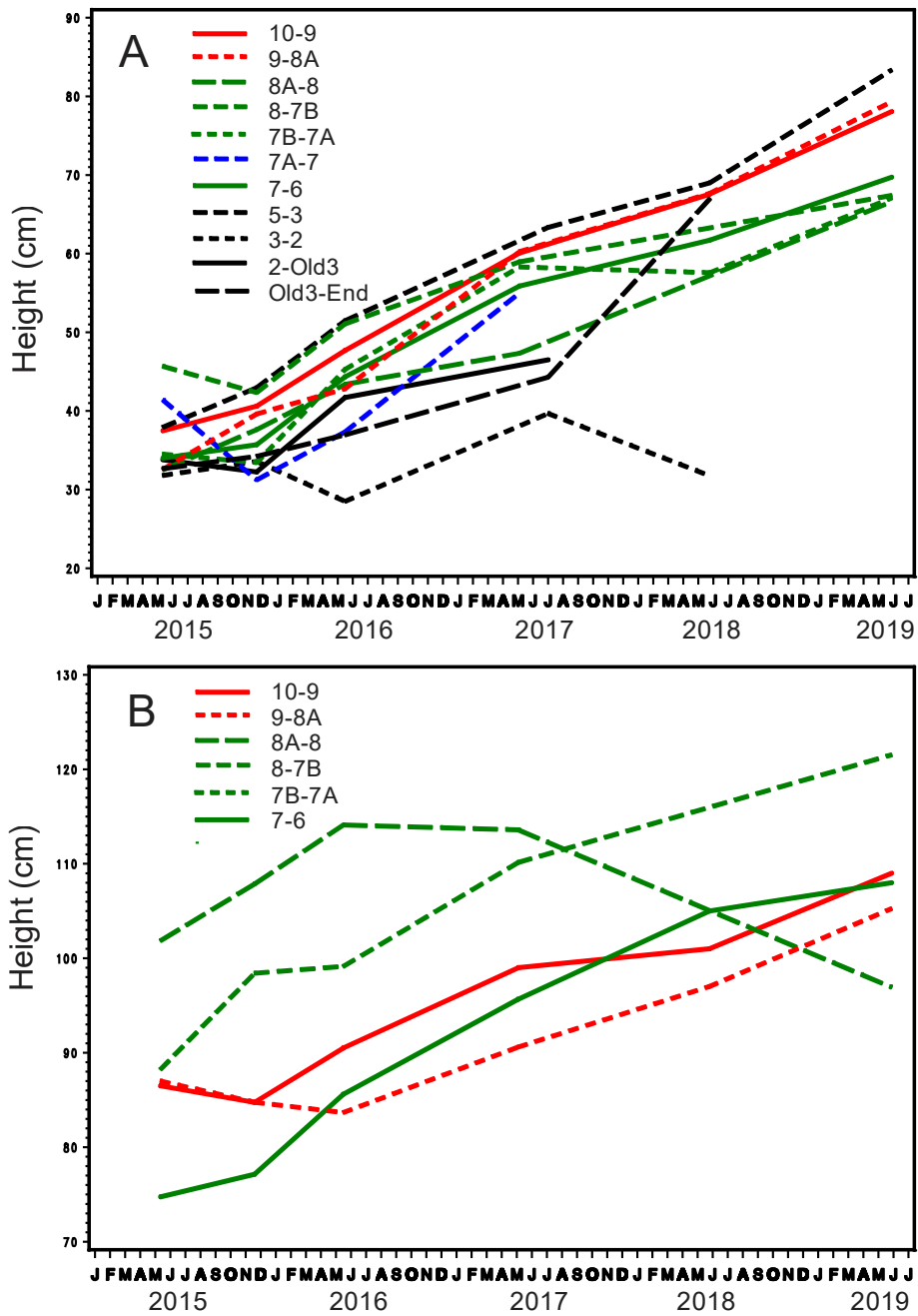


Figure 26. Growth of A. small (<<1 m in 2015) and B. large (~1 m in 2015) mangroves in different regions at Lang Lang South.

Seeds

Seeds with the highest survival, especially over the first 100 days, were planted at Grantville in January 2018. These seeds were attached to stakes by rubber bands (Figure 26A, Table A5). Staked seeds that were protected after April by short tubes also had higher survival than unprotected staked seeds (Figure 26A). But the growth rate of staked seeds was lower than that of all other methods trialled (Figure 26B).

Staking seeds markedly improved their survival over their first 100 days, as the stakes held them firmly in place. Many of the seeds planted with other methods washed away and some, which were buried too deeply, rotted. Staking seeds ensured no seeds washed away and gave greater control over the depth of planting, so that few rotted. However, survival of staked seeds was

very low at Lang Lang South (<5% in first 100 days, Table A5D), as fluid sediment below the seeds washed away leaving the seeds suspended 2 cm above the sediment.

The low growth of seeds attached to stakes by rubber bands was probably due to rubber bands inhibiting the normal growth of cotyledons. Rubber bands often held the seeds beyond the time they were well anchored by their own roots. This caused some cotyledons to become distorted by the rubber bands, and may have inhibited their growth.

The staking method clearly improves early survival, and further trials are desirable to develop a means of attaching seeds to stakes that does not reduce their subsequent growth, as survival may be greater for larger seedlings.

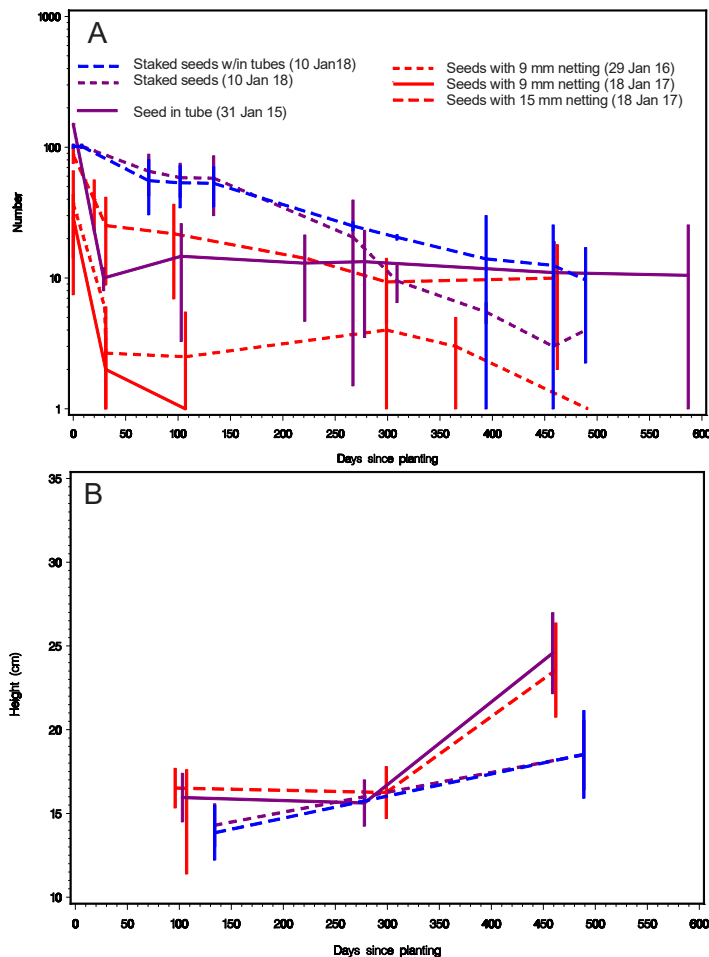


Figure 27. A. Survival, and B. Growth of mangrove seeds planted with different methods, for the first 600 days after planting. The dates of planting are shown in brackets. Error bars are standard errors.

Conclusions

Survival and growth of mangroves was lower at Lang Lang North than at Grantville and Lang Lang South. The low survival at Lang Lang North caused all planting since 2016 to be confined to Grantville and Lang Lang South. Once better methods of growing mangroves are available, further efforts to grow mangroves at Lang Lang North may be worthwhile.

Survival at Grantville and Lang Lang South was similar, despite mangroves having been removed from Grantville, but never having grown at Lang Lang South (Smythe 1842). This, and the low rate of natural recovery of mangroves at Grantville, suggests that removal of mangroves changes their habitat in ways that limit recruitment into the now mangrove-free habitat. Variation in survival between plots within these two sites was greater than variation between sites. Many of the factors responsible for this variation remain to be determined.

Mangroves planted further offshore usually had lower survival. Hurst et al. (2015) found a similar pattern, and it is likely that mangroves have more difficulty anchoring in softer sediments further offshore. This is likely to make establishing a broad band of mangroves more difficult.

The causes of mortality of mangroves at Grantville remain uncertain, although wave

energy is a major factor. Protection within tubes greatly increases initial seedling survival. Unfortunately until recently the tubes have themselves caused significant mortality when removed.

Survival was variable along the Lang Lang South coast, with strong growth and low mortality near the Lang Lang River and very low mortality in the NW of the two largest coves. Elsewhere adjacent to steep cliffs mortality was high, probably due to high wave energy, fluid sediments, or both.

It seems unlikely that mangroves will establish adjacent to steep cliffs at Lang Lang South without additional protection from waves, although it remains unclear how much mangrove mortality is directly due to waves. Soft fluid sediment looks to reduce survival adjacent to steep cliffs and the source of these soft sediments needs confirmation.

While the highest survival was achieved with 12 month old seedlings, high initial survival was also achieved with seeds. Further work is required to optimise the staked seed method as growing mangroves from seeds is much cheaper, making large-scale restoration more feasible. In addition, direct seeding does not rely upon expertise to on grow seedlings in a nursery for an extended period.

Acknowledgments

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Appendices

Table A1. Survival of seedlings planted at Grantville on different dates and using different treatments between 2015 and 2019. The number of survivors on each plot on each date is shown. The times tubes were removed and artificial turf attached are shown by coloured squares. The location of the plots are shown in Figure A1.

Date planted	Treatment	Plot No.	Date																							
			31-Jan-15	11-May-15	14-May-15	9-Sep-15	5-Nov-15	18-Nov-15	15-Jan-16	16-Apr-16	4-May-16	9-Sep-16	23-Nov-16	5-Dec-16	18-Jan-17	3-Apr-17	5-May-17	13-Nov-17	10-Jan-18	18-Jan-18	24-May-18	15-Nov-18	9-Feb-19	13-Apr-19	14-May-19	
31/01/2015	9-12m_seedlings	10	49	.	48	43	42	.	.	24	11	4	.	.	.	2	2	.	1	1
		14	48	.	47	42	40	.	.	37	35	30	.	.	.	23	21	.	21	19	13	.	.	12	5	
		16*	52	.	49	44	42	.	.	31	18	14	.	.	.	10	10	.	9	8	4	.	.	.	.
11/05/2015	3m_seedlings	6	.	96	93	56	46	.	.	13	0	0	.	.	.	.	.	.	.	.	.	.	.	.	.
		8	.	104	101	49	44	.	.	35	9	7	.	.	.	2	0	.	.	.	.	.	.	.	.
		12	.	101	88	26	24	.	.	13	1	0
	3m_seedlings (without tubes)	13	.	95	79	24	24	.	.	9	5	1	.	.	.	0
		17	.	99	98	42	29	.	.	18	11	5	.	.	.	5	1
		11	.	105	105	4	2
9	.	102	101	4	2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
18/11/2015	9-12m_seedlings	1	.	.	.	.	.	97	.	.	97	91	90	.	.	.	84	25	26	11	1	.	.	.	0
		11_replanted	.	.	.	.	.	70	68	.	59	46	39	.	.	7	0	0	0	0	.	.	.	.	.
		9_replanted	.	.	.	.	.	109	.	.	109	79	64	.	.	45	0	12	4	.	.	.	.	.	.
		A	.	.	.	.	.	100	88	.	73	39	29	.	.	7	0	0	.	.	.	.	.	.	1
C	.	.	.	.	.	100	85	.	74	42	25	.	.	16	11	12	3	3	.	.	.	1	.		
16/04/2016	3m_seedlings	B	.	.	.	.	.	.	.	100	84	55	52	.	.	.	42	14	10	1	1	.	.	0	.
		X	.	.	.	.	.	.	.	100	99	89	87	.	.	.	0	0	0	.	.	.	.	.
		Z	.	.	.	.	.	.	.	135	114	88	87	.	.	.	66	6	8	1	.	.	.	.
5/12/2016	9-12m_seedlings	P1#	.	.	.	.	.	.	.	.	.	.	.	100	.	.	46	21	23	16	15	.	.	15	
		P2	.	.	.	.	.	.	.	.	.	.	.	100	.	.	51	21	21	8	4	.	.	2	3
		P3	100	.	.	50	18	16	9	5	5	.	.	5	4
		P4	.	.	.	.	.	.	.	.	.	.	.	100	.	.	64	29	27	20	6	.	.	4	3
		P5	.	.	.	.	.	.	.	.	.	.	.	100	.	.	78	30	30	15	7	.	.	.	6
19/01/2017	9-12m_seedlings	P6	.	.	.	.	.	.	.	.	.	.	.	100	.	.	97	58	43	12	3	.	.	.	3
		P7	.	.	.	.	.	.	.	.	.	.	.	100	.	.	96	57	58	20	10	.	.	4	4
		P8	.	.	.	.	.	.	.	.	.	.	.	100	.	.	83	32	31	18	10	.	.	8	7
		P9	.	.	.	.	.	.	.	.	.	.	.	78	.	.	66	28	27	12	2	.	.	2	2
		P10	100	.	.	91	34	36	9	1
			100	.	.	91	34	36	9	1

* Only half of tubes removed from this plot on 16 Apr16, excluded from analysis.
 # Excluded from analysis as many seedlings planted without tubes



 Dates when artificial turf was attached.
 Dates when tubes were removed

Table A2. Survival of seedlings planted at Lang Lang North using seedlings of different ages and different planting methods between 2015 and 2017. The number of survivors on each plot on each date is shown. (Note: 9-12m seedlings +c, refers to seedlings planted inside milk cartons within protective PVC tubes). No seeds or seedlings were planted in Plot 9.

Date planted	Treatment	Plot No.	Date									
			28-Jan-15	27-Apr-15	13-May-15	10-Sep-15	6-Nov-15	4-Feb-16	2-May-16	9-Sep-16	2-Jul-17	13-Nov-17
28/01/2015	9-12m seedlings	12	50	.	46	33	22	15	9	2	.	.
		18	50	.	47	27	17	6	3	0	.	.
	9-12m seedlings+c	4	50	.	47	35	24	16	21	0	.	0
		17	100	.	98	63	26	12	9	1	.	.
27/04/2015	3m seedlings	21	50	.	50	46	28	.	7	0	.	.
		1	.	106	103	57	49	.	45	34	12	9
		2	.	100	96	74	68	.	62	3	2	1
		3	.	99	98	61	51	.	48	5	2	1
		6	.	99	98	60	50	.	40	20	4	.
		7	.	96	93	48	35	.	19	9	.	.
		8	.	98	97	55	38	.	15	3	.	.
		10	.	97	96	81	66	.	42	20	.	.
		13	.	99	91	59	44	.	20	4	.	.
		14	.	96	91	65	48	.	12	2	.	.
		15	.	90	88	62	45	.	17	0	.	.
		19	.	101	100	69	52	.	15	0	.	.
		20	.	100	89	48	29	.	15	3	.	.
		22	.	88	81	43	34	.	21	0	.	.
		A	.	106	103	65	58	.	55	39	16	1
C	.	90	78	44	36	.	29	1	0	0		
E	.	98	94	66	50	.	26	9	.	.		
F	.	97	94	57	36	.	23	3	.	.		
G	.	101	100	77	63	.	21	.	.	.		
H	.	100	96	55	42	.	13	3	.	.		
J	.	89	76	35	24	.	6	1	.	.		

Table A3. Survival of seedlings planted at Lang Lang South on different dates using seedlings of different ages and different planting methods between 2015 and 2019. The number of survivors on each plot on each date is shown. Dates tubes were removed, or artificial turf was added, are shown by the coloured squares.

Date planted	Treatment	Plot No.	Date																
			1-Nov-14	12-May-15	19-Nov-15	14-Apr-16	16-May-16	16-Sep-16	22-Nov-16	17-Jan-17	17-Feb-17	2-Apr-17	4-May-17	14-Nov-17	9-Feb-18 & 23-Apr-18	25-May-18	14-Nov-18	12-Apr-19	13-May-19 28-May-19
1/11/2014	9-12m seedlings+cartons	St_Josephs Crib Pt	230	101	28	.	11	.	.	.	.	.	.	.	0	.	.	.	.
14/04/2016	3m seedlings	S1	.	.	.	100	95	78	75	.	.	38	9	2	.	.	.	.	.
		S2	.	.	.	103	103	91	82	.	.	.	71	64	49	50	.	.	20
		S3	.	.	.	100	95	92	77	.	.	62	28	19	.	.	.	.	7
		S4	.	.	.	100	25	18	12	.	.	.	10	10	7	7	4	.	2
		S5	.	.	.	100	76	36	28	.	.	19	2	0	.	.	.	.	.
		S6	.	.	.	100	99	91	81	.	.	71	64	23	.	.	.	.	.
		S7	.	.	.	100	99	96	92	.	.	.	75	32	4	0	.	.	0
		SA	.	.	.	98	98	95	94	.	.	82	22	2	.	.	.	0	0
		SB	.	.	.	100	.	94	86	.	.	55	51	28	2	1	.	1	1
		SC	.	.	.	100	80	63	50	.	.	.	20	11	6	2	2	.	0
		SD	.	.	.	100	94	69	63	.	.	.	49	29	11	6	.	.	1
		SE	.	.	.	100	62	50	31	.	.	15	14	4	0	.	.	.	.
		SF	.	.	.	100	66	29	11	.	.	6	0	.	0	.	.	.	.
		SG	.	.	.	100	22	8	2	.	.	.	.	.	0	.	.	.	.
SH	.	.	.	100	36	6	4	.	.	.	3	.	0	.	.	.	.
17/01/2017	9-12m seedlings	P1	.	.	.	.	.	.	100	.	.	86	40		22	3	2	0	
		P2	.	.	.	.	.	.	100	.	.	84	33		13	13	9	2	
		P3	.	.	.	.	.	.	.	100	.	.	88	31		21	11	9	4
		P4	.	.	.	.	.	.	.	100	.	.	94	82		78	54	43	11
		P5	.	.	.	.	.	.	.	100	.	.	77	25		10	2	2	0
		P6	.	.	.	.	.	.	.	.	100	.	63	28		15	2	3	2
		P7	.	.	.	.	.	.	.	.	100	.	32	7		.	.	.	0
		P8	.	.	.	.	.	.	.	.	100	.	94	76		52	32	32	4
17/02/2017	9-12m seedlings	P11	.	.	.	.	.	.	.	100	.	49	4		6	3	1	1	
		P12	.	.	.	.	.	.	.	105	.	101	86		57	24	4	0	
		P13	.	.	.	.	.	.	.	104	.	98	92		91	89	.	23	



 Date protective tubes removed
 Date artificial turf attached to tubes

Table A4. Number of small and large (>1m high) mangroves on regions of Lang Lang South foreshore between May 15 and May 19.

Region	Plant size	Date						
		12-May-15	19-Nov-15	16-May-16	4-May-17	1-Jul-17	25-May-18	28-May-19
10-9	Large	1	3	1	2	.	2	3
	Small	155	124	127	103	.	96	.
9-8A	Large	3	3	3	4	.	4	3
	Small	87	60	57	41	.	31	33
8A-8	Large	21	19	22	20	.	.	18
	Small	6	9	9	6	.	.	6
8-7B	Large	37	32	27	18	.	.	24
	Small	83	95	92	113	.	.	107
7B-7A	Large	0	.	.	.	.	.	5
	Small	111	104	101	98	.	95	91
7A-7	Large	1	.	.	.	.	.	.
	Small	27	12	6	1	.	.	.
7-6	Large	17	16	14	6	.	6	8
	Small	95	89	93	92	.	96	91
6-5	Large	0	.	.	.	.	.	.
	Small	0	.	.	.	.	.	.
5-3	Small	43	23	17	.	11	8	3
3-2	Small	15	7	7	.	6	4	0
2-Old3	Small	61	25	19	.	4	.	0
Old3-End	Small	101	34	28	.	7	1	0

Table A5. Survival of seeds planted at Lang Lang North, Lang Lang South and Grantville on different dates using different planting methods between 2015 and 2019. The number of survivors on each plot on each date is shown.

A. Seeds planted January 2015. Treatment: Seeds pressed into sediment within slotted tubes

Site	Date planted	Treatment	Plot Number	Date																	
				28-Jan-15	31-Jan-15	1-Mar-15	13-May-15	14-May-15	9-Sep-15	10-Sep-15	5-Nov-15	6-Nov-15	4-Feb-16	2-May-16	4-May-16	9-Sep-16	23-Nov-16	5-May-17	13-Nov-17	18-Jan-18	
Grantville	31/01/2015	Seeds without mesh	15	.	150	.	.	26	21	.	23	.	.	.	19	18	13	10	.	.	
			18	.	150	11	.	10	11	.	10	.	.	.	7	3	4	4	4	2	.
			7	.	150	9	.	8	7	.	7	.	.	.	7	0	0
Lang Lang North	28/01/2015	Seeds without mesh	11	150	.	26	26	.	.	26	.	23	.	15	.	7	.	.	.	.
			16	150	.	8	7	.	.	6	.	5	.	3	.	1	.	.	.	.
			5	150	.	23	19	.	.	18	.	14	12	12	.	1	.	.	.	.

B. Seeds planted January 2016. Treatment 9 mm meat netting (double layer)

Site	Date planted	Treatment	Plot Number	Date															
				15-Jan-16	26-Jan-16	29-Jan-16	4-Feb-16	8-Feb-16	18-Feb-16	29-Feb-16	2-May-16	4-May-16	9-Sep-16	23-Nov-16	5-May-17	13-Nov-17	18-Jan-18		
Grantville	15/01/2016	9 mm meat netting	15 (reseeded)	95	87	.	60	.	.	56	.	50	.	.	.	.	.	.	.
			7 (reseeded)	.	.	93	.	.	59	26	.	20	.	6	0	.	.	.	.
			D	.	.	69	.	.	21	16	.	16	14	8	6	2	2	.	.
			E	.	.	78	.	.	33	19	.	17	.	14	14	.	.	.	.
			F	.	.	101	.	.	25	9	.	6	.	.	.	.	.	.	.
Lang Lang North	4/02/2016	9mm meat netting	5 (reseeded)	.	.	.	79	.	62	18	12	.	7	.	.	.	0	.	

C. Seeds planted January 2017. Treatments: 9 mm meat netting (single layer) and 15 mm meat netting

Site	Date planted	Treatment	Plot Number	Date											
				17-Jan-17	18-Jan-17	17-Feb-17	18-Feb-17	4-May-17	5-May-17	13-Nov-17	14-Nov-17	18-Jan-18	24-May-18		
Grantville	18/01/2017	15mm meat netting	13 (reseeded)	.	19	.	0	.	0	1
			6 (reseeded)	.	24	.	0	.	0	0	.	0	0	.	
			8 (reseeded)	.	51	.	1	.	1	0	.	0	0	.	
		9 mm meat netting (single layer)	D (reseeded)	.	22	.	3	.	.	.	.	.	.	.
			12 (reseeded)	.	16	.	1	.	0	0	.	.	.	.
			17 (reseeded)	.	18	6	.	.	1	1	.	2	1	.	
			7 (reseeded2)	.	79	.	1	.	0	0	.	0	0	.	
			E_all	.	.	.	.	.	.	7	.	4	.	.
			E_reseeded	.	34	.	6	.	4	.	.	.	0	.	
Lang Lang South	17/01/2017	15 mm meat netting	P10	50	.	10	.	3	.	.	3	.	.		
			P14	52	.	16	.	4	.	.	1	.	.		

D. Seeds planted January and February 2018. Treatment: staked seeds

Site	Date planted	Treatment	Plot Number	Date														
				10-Jan-18	18-Jan-18	9-Feb-18	23-Mar-18	22-Apr-18	23-Apr-18	24-May-18	25-May-18	4-Oct-18	14-Nov-18	15-Nov-18	8-Feb-19	13-Apr-19	14-May-19	28-May-19
Grantville	10/01/2018	Staked seeds	12 (+tubes)	100	100	.	43	44	.	44	.	26	.	21	22	19	17	.
			13 (- tubes)	100	100	.	54	50	.	44	.	11	.	8	6	.	7	.
			2 (-tubes)	104	104	.	77	67	.	72	.	30	.	11	5	3	4	.
			3 (+tubes)	103	103	.	68	63	.	62	.	24	.	20	6	6	5	.
Lang Lang South	9/02/2018	Staked seeds	P10 (-tubes)	.	.	100	26	.	.	.	3	.	0	.	.	.	.	.
			P9 (-tubes)	.	.	100	46	.	1	.	1	.	1	.	.	.	0	.
			S1 (+tubes)	.	.	100	46	.	5	.	5	.	2	.	.	.	.	.
			S5 (-tubes)	.	.	100	55	.	.	.	10	.	0	.	.	.	.	.